Experimental Research on Mechanical Properties of Apple Peels

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Abstract. Knowledge of the mechanical properties of apple peel, as the outermost tissue of the fruit, is crucial for the designing of apple harvesting machines. In this study, longitudinal and transverse tensile tests were conducted on peels from the shadow side and sunlit side of two apple cultivars (Starkrimson and Fuji) using an electronic universal testing machine, and tear tests and puncture tests were carried out on peels of both sides as well. The stress-strain curves and tear and puncture force-deformation curves of the peels were acquired and the tensile strength, elastic modulus, failure strain tear strength, puncture strength of the peels were measured. Also, scanning electron microscope images were made. The results showed that the maximum values of tensile strength, elastic modulus, fracture strain, tear strength, and puncture strength were 2.56 MPa, 24.00 MPa, 19.92%, 0.391 $kN{\cdot}m^{-1}$, and 0.289 $N{\cdot}mm^{-2}$, respectively. The tensile strength, elastic modulus, and puncture strength values for the Starkrimson peels were higher than those for the Fuji peels from the same side. Apple peel is an anisotropic heterogeneous material. The bearing capacity of the peel depends on the number and distribution of microcracks on the surface, and the size and shape of the epidermal cells. The organization and connections between the cells determine the strength of the connections between cells.

Keywords: *apple; experiment; mechanical properties; peel; research.*

1 Introduction

The mechanical properties of fruit peel are an important reference for harvesting, processing, packaging, storing and transporting the fruit. Also, the peel has a strong resistance to microbial infection and mechanical damage.

Singh and Reddy [1] researched which orange handling, packaging, storage and transportation systems to adopt, and how to design them. They investigated the mechanical properties of orange peel under ambient and refrigerated fruit storage conditions and carried out a tensile test and a cutting test. Allende*, et al.* [2] isolated different sections of the tomato pericarp and used a universal testing machine to gain a better understanding of puncture injury susceptibility of

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tomatoes under tensile stress. They evaluated the skin tissue with light microscopy to determine its geometrical properties. The researchers discovered that puncture injury susceptibility increased when the rupture stress of the skin and the thickness of the cuticles decreased during the storage process and that differences in microstructure appear to influence the strength of the tomato skin. Andrews, *et al.* [3] used an Instron universal material testing instrument to investigate the mechanical properties of tomato skins mediated by peroxidase at different ages. They found that the application of peroxidase from the cell walls of mature tomato fruit skin changed the mechanical properties of the fruit. To ascertain the suitability of five tomato cultivars for industrial processing and fresh consumption, Hetzroni, *et al.* [4] examined the mechanical properties of ripe tomato peels under uniaxial tension and puncture tests. In order to foster good varieties of grapes and tomatoes, and estimate the resistance of grapes and tomatoes to cracking, Wang, *et al.* [5] investigated grape and tomato peels in a tensile test and concluded that grape skin and tomato skin are isotropic materials. The strength of the grape skin and the tomato peel could reduce mechanical damage. Eckhard, *et al.* [6] executed a tensile test on apple peel regions with and without skin spots after the apples were held in refrigerated storage for a minimum period of 14 days. They found that strips of fruit skin from regions with skin spots had an increased maximum force and modulus of elasticity.

The texture of the peel is one of the primary quality attributes of a fruit and the microstructure of the peel is closely related to its mechanical properties. Deng Jiguang, *et al.* [7] researched the structure of 25 species of apples and found that when the skin's organization structure has certain characteristics – i.e. the peel is thick, the cells have many layers, the cells are long and thin and closely packed – the protection and extrusion characteristics of the peel are better. Oey, *et al.* [8] investigated the influence of turgor on the micromechanical properties of two apple cultivars and the structural parameters of their cells through uniaxial tension and compression. They concluded that the strain at maximum stress was significantly lower, while the stiffness increased with the increase of turgor. Manipulation of the turgor did not affect the initial cell parameters. Alamar, *et al.* [9] examined the micromechanical behavior of apple parenchyma of two different cultivars under two storage conditions through uniaxial tension and compression testing. They found no differences in the mechanical parameters of both cultivars, but a significant storage effect was discovered. They reported that the relationship of mechanical properties at the micro- and macro-level were different.

In two other studies, Wang Jun, *et al.* [10,11] used compression and relaxation tests with different sampling parts, direction, depth, and direction of pear flesh specimens. They found that differences in mechanical properties between different sampling parts affect the processing process of the pear peel and the classification of intact pears.

The microstructure of apple peel in relation to its mechanical properties have not yet been investigated. In this paper, a study is presented that was focused on the mechanical properties and microstructure of the peel of two kinds of apples. It appraises the mechanical attributes of the fruit peel for the shadow and the sunlit side of the samples, it shows differences in the structural parameters of the peel and it describes the effect of the microstructure of the peel on its mechanical properties. The objectives of this study were to provide a reference for: (1) the selection method in relation to the harvesting, processing, packaging, storing and transporting of apples; the designing of related mechanical equipment; and depth development of apple products; (2) to provide knowledge for better cultivation of the apple fruit and evaluation of the apple peel; (3) to do some fundamental work in support of biomimetic materials prototype selection for water resistance of fruit and vegetable skin packaging.

2 Materials and Methods

2.1 Fruit Selection

The peels of Fuji and Starkrimson apples were selected as the testing materials. The apples were purchased from the Institute of Pomology, Shanxi Academy of Agricultural Sciences on October 23, 2013, and were placed in the laboratory refrigerator at a storage temperature of about 3~5°C.

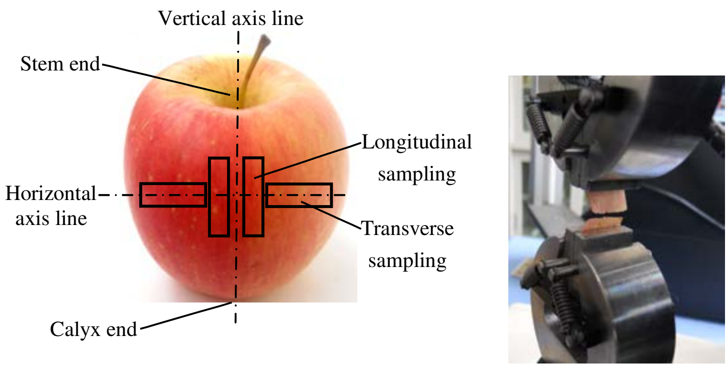
For the tests, regularly shaped apples were selected to ensure that there would be no pests on the different parts of the peels, there would be no mechanical damage to the fruit, and the peel surface of both sides could be obviously distinguished. The longitudinal and transverse diameters of the Fuji apples ranged between 61.8~64.5 mm and 74.5~78.9 mm, respectively. The longitudinal and transverse diameters of the Starkrimson apples ranged between about 61.2~63.8 mm and 72.2~ 76.4 mm, respectively.

As is known to all, Fuji and Starkrimson are two main varieties of apple cultivation in China [12]. Fuji and Starkrimson apples both belong to the late-maturing variety [13]. They have good storage resistance under conditions of a controlled storage atmosphere. The storage period of Fuji apples can reach 8 months, while still maintaining good quality [14,15]. The storage period of Starkrimson apples can reach up to 6 months [16,17]. We selected these two apple cultivars because the differences in microstructure and storage period between Fuji and Starkrimson apples are known [18].

2.2 Mechanics Tests and Experiments

2.2.1 Tensile Test

The samples were tested on two parts of the peridermal segment of the fruit, shadow side and sunlit side, according to the standard test conditions specified in the standard document GB/T 1040.3-2006 *Plastics –Determination of Tensile Properties–Part 3: Test Conditions for Films and Sheets* [19]. Longitudinal and transverse samples were simultaneously collected from each side of the peel (as shown in Figure 1(a). The peel was removed from the sampling fruit with a razor blade and placed on a smooth rubber mat and then put under a magnifying glass. The flesh was then scraped gently from the peel to ensure it would not be damaged, after which specimen strips were made with a size of 40 × 15 × t mm (t is the thickness of the sample rind). Hetzroni, *et al.* used razor blades to obtain mechanically peeled tomato skin, which was then made into specimens for a tensile test [4]. To avoid stress concentration, the grape, tomato and orange peels in [1,3,5] were cut into rectangular samples for a tensile test.



(a) Sampling directions (b) Tensile test

Figure 1 Specimens and tensile test.

The mechanical properties of each apple peel sample were measured with a universal testing machine (INSTRON-5544, England) equipped with wedge clamps for tensile testing (as shown in Figure 1(b)). The peel specimen thickness (t) was measured by a grating thickness measurement device (JC010-1, China). The peel thickness of the Fuji and Starkrimson samples ranged from 0.213~0.224 mm and 0.208~0.221 mm, respectively. In order to prevent loss of moisture content, the peel test specimens were put on the test tag immediately. The acceleration speed of the tensile test was 1 mm/min. Original specimen stretching was measured using vernier calipers with a resolution of 0.01 mm. In the peel specimen tensile experiments, the original gauge length range of the Fuji and Starkrimson apples were measured as 9.98~10.03, 9.98~10.04 mm, respectively.

The apple peel being the outermost layer of the fruit, its mechanical properties such as elastic modulus, tensile strength and other indicators can be used to predict the extent of damage and destruction to the fruit in the process of harvesting, packaging, storage and transportation, etc. The modulus of elasticity (E, Pa) is taken as an important indicator of the peel's elastic deformation. From the peel stress-strain curve, the maximum slope value can be obtained [6]; the calculation formula is expressed as $E = F\Delta l/(A_0 l)$ [4], where F represents the axial tensile specimen force, A_0 represents the original cross-sectional area of the sample, and Δl, l represent the elongation of the specimen when it is stretched and the standard distance. The tensile strength (σ, Pa) is an important evaluation index of peel damage or destruction. The corresponding stress values can be obtained from the breaking point of the peel stress-strain curve; the calculation formula is given by $\sigma = F_\sigma/A_0$ [1,4], where F_σ represents the amount of force at which the specimen starts to fracture.

2.2.2 Tear Test

The fruit peel is the outermost layer of a thin film material and is under the effect of internal and external load in the process of the growth of the fruit. The pros and cons of internal fruit quality can not only be characterized by the tensile strength index of the peel but also peel tear strength can be used. In order to further compare the quality of the peel material, in this study a tear test was carried out to investigate the peel.

According to the document GB/T 16578.1-2008 *Plastics – Film and Sheeting – Determination of Tear Resistance – Part 1: Trouser tear method* [20], apple peel samples were obtained from the sunlit and shadow side of the fruit respectively, cut longitudinally and long-strip specimens with a size of 30 × 15 × t mm were made (t denotes the peel specimen's thickness). The sample was tested with a universal testing machine. A 15-mm incision was made in the direction parallel to the longitudinal axis of the sample, after which the formed two leg notches were subjected to a tensile test (as shown in Figure 2). A magnifying glass was used to ensure the smoothness of the incision. The apple peel thickness of both apple varieties was measured by raster thickness gauge. The thickness was 0.191~0.212 mm for the Fuji apples and 0.183~0.215 mm for the Starkrimson apples. In the tear test, the loading speed was about 20 mm/min. The average values for the sunlit and the shadow side of the peels obtained were calculated from 15 replications.

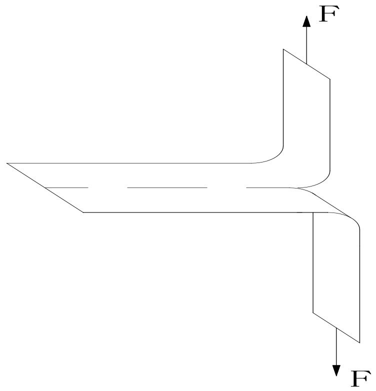


Figure 2 Trouser tear test diagram.

According to the standard document GB/T 3917.2-2009 *Textile Fabric – Tearing Performance – Part 2: Breeches Sample (Single Slit) Determination of the Tear Strength* [21], if the tear curve has many peaks, it can be divided into four areas from the first peak to the last peak. In regions 2, 3 and 4, the two lowest peak and two highest peaks are selected, and the average value of 12 peak loads is the tear force of the sample. The calculation formula for the tear strength (T , $N \cdot m^{-1}$) is given by $T = F_T/d$, where F_T represents the force of the tear sample and d represents the original thickness of the sample.

2.2.3 Puncture test

It is generally known that during post-harvest handling, apple fruit is submitted to mechanical stress causing peel puncture injuries. Therefore, puncture tests were carried out to determine differences in injury susceptibility of the various apple peels. Samples of the sunlit and the shadow side of the apple's surface with a size of 24 × 24 × t mm (t denotes the thickness of the sample) were made for the puncture test according to the standard document HG/T 3839-2006 *Plastic – Shear Strength Test Method of Perforation Method* [23]. In [4], circular specimens produced with a razor blade were used in puncture tests of various tomatoes peels. Using a raster thickness gauge, the thickness of the puncture specimens was measured between 0.172~0.203 mm for the Fuji apples and 0.160~0.186 mm for the Starkrimson apples. Using the perforation method from [23], a set of jigs was designed, formed by the perforation and film composition as shown in Figure 3, according to HG/T 3839-2006-plastic shear strength test method. The perforator was fixed to a universal testing machine, with the sample fixed between the upper and lower film during the test fixture. The radius of the upper and lower punch was 2 mm, while the test speed was 1 mm/s. The average values are reported of 15 replications for the sunlit and the shadow side of the apple peels, respectively.

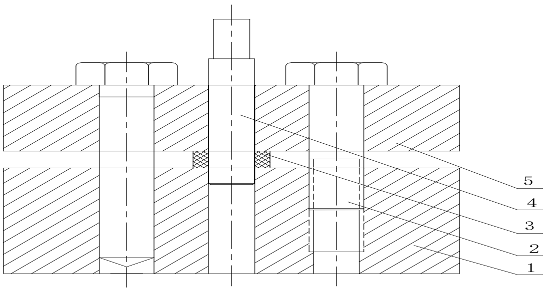


Figure 3 Grips for puncture of apple peels. 1 = bottom model, 2 = bolt, 3 = sample, 4 = punch, 5 = upper model.

The puncture strength (P, $N \cdot m^{-2}$) is taken as an indicator of the puncture or rupture resistance of the peel samples. Its value can be obtained from the rupture point of the peel puncture curve. The calculation formula for the puncture strength is $P = N_P / A$, where N_P represents the force at which the sample is perforated, while A represents the force area in which the sample is perforated.

2.3 SEM Sample Observation

Tissue blocks (fruit sections) were cut from the periderm of the shadow and the sunlit side of the fruit. Then the samples were fixed with a 3% solution of glutaraldehyde, i.e. a mixture of 0.1 M phosphate buffer (pH 7.2), at a low temperature (0~4°C) for 2 h. Then the segments were washed three times with the same buffer for 15 minutes per session and dehydrated in ethanol series with a composition of 30%, 50%, 70%, 80%, 90%, and 95% ethanol for 20 minutes each time. They were displaced by tert-butyl alcohol and freeze-dried by a JEOL JFD-320 instrument. Finally the samples were coated with platinum using a JEOL JFC-1600 Sputter Coater and observed using a JEOL JEM-6490 LV scanning electron microscope.

In order to obtain the precise relationship between macro-mechanics and microstructure, the SEM samples were subjected to mechanics tests and were immediately handled and examined using a scanning electron microscope after the mechanics tests were performed.

2.4 Statistical Analysis

Mechanical parameters of the peel samples, i.e. maximum load, tensile strength, elastic modulus, fracture strain, tear force and puncture force, were measured with a computer-controlled universal testing machine. For statistical analysis, the results were subjected to Duncan's multiple range test in the ANOVA procedure of SAS, version 8 (SAS Institute, Cary, NC, USA) with a 95% confidence interval. The microstructure indexes of the peels were measured using MATLAB, version 7 (Mathworks, Natick, USA).

3 Results and Discussion

3.1 Tensile Test

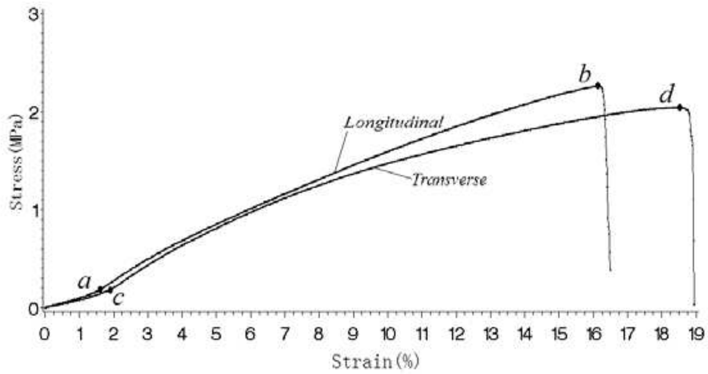


Figure 4 Stress-strain curve of apple peel tensile test.

The stress-strain curves of longitudinal and transverse samples of the Fuji apple peel from the sunlit side are shown in Figure 4. As can be seen from Figure 4, the stress-strain curves have a nonlinear S-shape. They are composed of two sections. The first part is an approximately straight line segment (oa section and oc section), where the stress increases faster than the strain. The reason is that when the strip sample is unstretched, it is in a micro-buckled state. However, the tensile strain being large in the initial part, the stress displays an uneven distribution and as a peel tissue cell gap exists, the peel tissue cells will be reoriented in the first segment [24]. In the second curve segment (ab section or cd section), as the peel buckling in the direction of the sample gradually disappears, the peel force displays a more uniform stress distribution, with an increase of stress and strain. At point b (or point d), the stress reaches maximum value. After that the peel sample will fracture gradually but the stress does not decrease to zero rapidly. It decreases gradually and the curve has a smaller extension. In the tensile test process, it was observed that the fruit peel specimen broke at fruit spots (formed by young fruit epidermis pores that are filled with phellem during the fruit maturing period [25,26]) and extended gradually from there. The fruit spots being stress concentration points, the fracture in the surface of the specimen will pass through the various fruit spots, as shown in Figure 5.

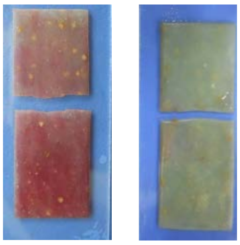


Figure 5 Fracture samples of apple peel.

The same characteristics of the stress-strain curves were observed in the Starkrimson apple samples. Similar stress-strain curves produced by tensile testing were found in [8,9] and the tissue curves show that the stress was low for small strain and increased with the increase of strain.

For four parts of peel – i.e. sunlit longitudinal, shadow longitudinal, sunlit transverse and shadow transverse – the results obtained in the maximum load test, tensile strength test, elastic modulus test and failure strain test were as shown in Table 1.

Table 1 Mean value and standard error of mechanical properties of apple peels under tensile loading.

Breed	Parts	Maximum load/N	Tensile strength (MPa)	Modulus of elasticity (MPa)	Failure strain (%)
Fuji	Sunlit longitudinal	6.99±0.94	2.15±0.29	19.61±2.22	15.83±2.87
	Shadow longitudinal	6.67±0.68	2.06±0.20	22.61±2.95	14.19±3.11
	Sunlit transverse	6.15±0.68	1.90±0.23	18.23±2.26	16.27±2.84
	Shadow transverse	6.14±0.95	1.86±0.26	17.79±4.00	16.93±4.89
Star-krimson	Sunlit longitudinal	8.27±0.71	2.56±0.22	24.00±3.95	18.32±2.38
	Shadow longitudinal	7.61±0.70	2.33±0.24	23.98±4.32	17.66±2.26
	Sunlit transverse	7.84±0.80	2.39±0.28	21.27±3.92	19.92±4.64
	Shadow transverse	7.58±0.94	2.35±0.19	21.72±2.85	19.67±2.99

In Table 1, it can be seen that for different parts of the apple, the skin tensile mechanical properties are different. The calculated mean value of tensile strength for the four parts of the Fuji samples ranged from 1.86 MPa to 2.15 MPa, while the Starkrimson samples ranged from 2.35 MPa to 2.56 MPa.

The sunlit longitudinal sample of each cultivar had the highest tensile strength of the four parts of the peel. And it was also found that the Starkrimson variety had higher tensile strength than the Fuji variety in the same part.

As for the four parts of the Fuji samples, the calculated mean elastic modulus ranged from 17.79 MPa to 22.61 MPa, while for the Starkrimson samples it ranged from 21.27 MPa to 24.00 MPa. Within the same cultivar, the longitudinal elastic modulus was higher than the transverse elastic modulus for the same side. Eckhard, *et al.* did research on Elstar apple peel that was stored for a period of 14 days and found that the elastic modulus of Elstar peel with skin spots was higher than that of peel without skin spots under tensile tests; the values ranged from 30.5 Mpa to 50.6 Mpa [6]. In fact, the tensile strength and elastic strength obtained from the apple tissue that was subjected to the tensile test were small values, smaller than those of the apple peel [8,9]. This typifies the peel as the outermost layer of a fruit, protecting it from damage or destruction, but different peels have different mechanical properties.

Using the tensile test data, the tensile strength and elastic modulus of both cultivars were compared with an independent sample t-test [28]. There were significant differences ($p \le 0.05$) in tensile strength and elastic modulus on corresponding parts of the Starkrimson and the Fuji samples. The variance analysis showed that Starkrimson peel has obviously better material mechanical properties than Fuji peel; its ability to resist horizontal and vertical deformation is higher than in the case of Fuji peel. For each cultivar, the tensile strength and elastic modulus of the longitudinal samples showed significant differences ($p \le 0.05$) with those of the transverse samples. This analysis shows that the apple peel is an anisotropic heterogeneous material and in order to reduce damage, it should be considered that clamping the fruit longitudinally is the best option when designing an apple-harvesting machine. At the same time, from Table 1, it can be observed that the transverse fracture strain is higher than the longitudinal fracture strain for the same cultivar, but no significant difference between them was found. It is noted that the expansibility of the longitudinal samples was superior to that of the transverse samples.

3.2 Tear Test

The tear load-displacement curve of the sunlit Fuji apple peel is shown in Figure 6. As the figure shows, the peel tear curve is a curve with many peaks. The destruction of the sample starts from the incision in the process of the tear test and there is a linear stretch back from the incision. The form of the curve is caused by the two legs of the sample being separated on the test machine. The incision as stress concentration place is the starting point of the tearing of the peel. The medium between the peel cells produces relative slip between connected cells. When the slip reaches the limit, the connected cells begin to be stripped apart and a peak in the tear curve is formed. The other peaks in the curve are formed as connected cells behind the starting point are stripped apart in succession. At the same time, during tearing the medium between the cells that are not stripped also produces loads. These loads form the peak valleys of the curve.

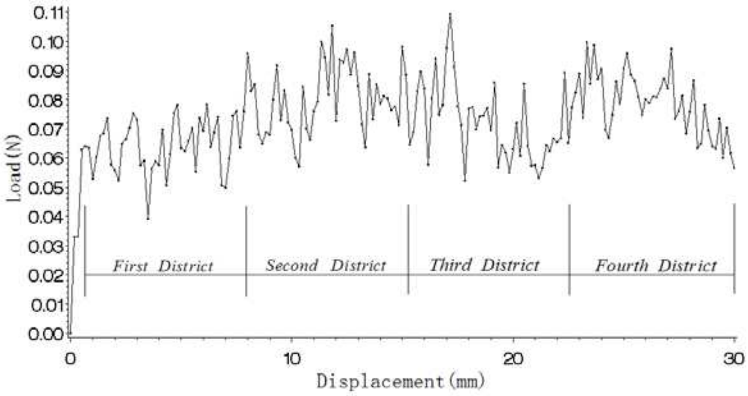


Figure 6 Force-deformation curve of tear test of apple peel.

Table 2 Mean value and standard error of torn strength of apple peels.

Sample number	Tear force /N				Tear strength /$kN{\cdot}m^{-1}$			
	Red Fuji sunlit	**Red Fuji shadow**	**Star-krimson sunlit**	**Star-krimson shadow**	**Red Fuji sunlit**	**Red Fuji shadow**	**Star-krim-son sunlit**	**Star-krimson shadow**
1	0.084	0.079	0.08	0.078	0.399	0.378	0.412	0.385
2	0.082	0.069	0.073	0.081	0.429	0.326	0.340	0.412
3	0.063	0.082	0.091	0.068	0.299	0.389	0.433	0.322
4	0.071	0.086	0.06	0.062	0.348	0.428	0.280	0.290
5	0.086	0.074	0.098	0.089	0.425	0.359	0.513	0.462
6	0.067	0.072	0.072	0.063	0.320	0.374	0.341	0.304
7	0.084	0.065	0.087	0.092	0.399	0.333	0.424	0.429
8	0.072	0.079	0.076	0.063	0.350	0.400	0.362	0.337
9	0.087	0.07	0.086	0.092	0.456	0.340	0.444	0.445
10	0.077	0.073	0.077	0.064	0.376	0.368	0.383	0.316
11	0.062	0.07	0.093	0.066	0.310	0.343	0.457	0.347
12	0.08	0.081	0.081	0.065	0.416	0.419	0.396	0.325
13	0.064	0.076	0.089	0.084	0.322	0.351	0.464	0.392
14	0.088	0.067	0.051	0.064	0.461	0.354	0.265	0.352
15	0.064	0.074	0.063	0.07	0.322	0.384	0.344	0.339
$\bar{X} \pm SD$	0.075±0.01	0.074±0.006	0.078±0.013	0.073±0.011	0.375±0.05	0.370±0.03	0.391±0.07	0.364±0.05

The tear force and tear strength values of two kinds of peel samples are shown in Table 2. The tear force of the peel was far smaller than the load values of the peel tensile fracture, so the conclusion can be drawn that the tearing failure mode of the peel is the main cell and cell stripping form and the peel failure mode of tensile fracture is the main cell stress fracture form at the same time. From the table, it can be seen that the average tear strength values of the sunlit peel samples were greater than those of the shadow peel samples in both apple cultivars, but no significant effect was observed. No significant effect was observed between both cultivars either.

3.3 Puncture Test

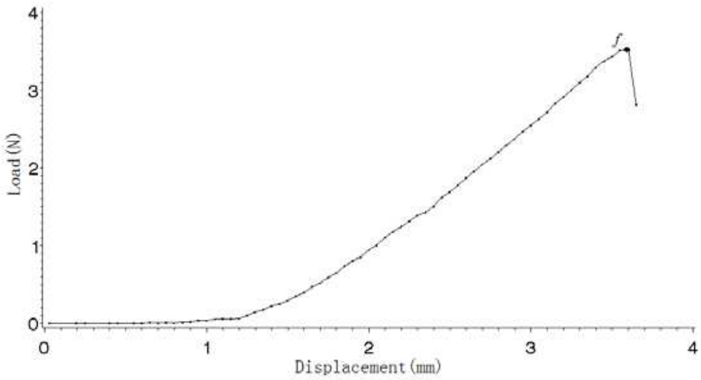


Figure 7 Force-deformation curve of puncture test of apple peel.

Figure 7 shows a typical result of the puncture load-displacement curve for the Starkrimson shadow peel. The peel puncture curve can be approximated by a straight line segment; f is the rupture point at which significant peel failure happened and its corresponding values can be used as puncture strength. In fact, Hetzroni, *et al.* stated that the puncture characteristics of circular specimens of fruit peel can be determined by a puncture strength test. A similar force-deformation curve generated by a puncture test was found for tomato peel. The upper part of the curve has a breaking force that can be represented by the puncture force [4].

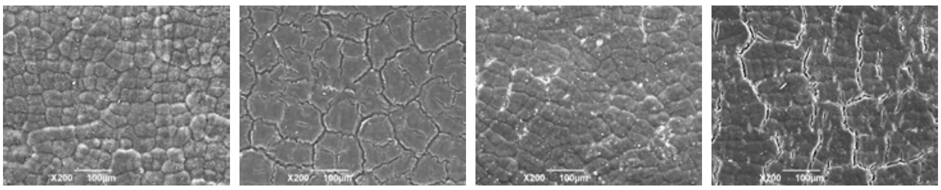
The puncture strengths of both kinds of apple peel are shown in Table 3. It shows that peel puncture strength ranged from 0.188 N/mm 2 to 0.289 N/mm2. As for the Fuji peel, the puncture strength of the sunlit samples was significantly larger than that of the shadow samples; a significant effect ($p \leq 0.01$) was observed. The difference in puncture strength between both sides of Starkrimson peel was relatively small, but there exists a significant difference ($p \leq 0.05$). From the table, it can also be seen that the Starkrimson apple has higher average puncture strength and there only exists a significant difference ($p \leq 0.05$) between the shadow side Starkrimson and Fuji peels. From the above analysis, it can be stated that as to the same kind of peel, the puncture properties of the sunlit side part are better than those of the shadow side part. As for the different cultivars, the puncture resistance ability of Starkrimson peel is superior to that of Fuji peel.

Table 3 Puncture strength of apple peels.

Sample number	Puncture Strength/$N \cdot mm^{-2}$			
	Fuji		Starkrimson	
	sunlit	shadow	sunlit	shadow
1	0.293	0.188	0.351	0.221
2	0.119	0.217	0.230	0.180
3	0.349	0.099	0.304	0.274
4	0.338	0.181	0.251	0.240
5	0.129	0.222	0.324	0.281
6	0.218	0.185	0.381	0.221
7	0.208	0.213	0.308	0.272
8	0.328	0.133	0.262	0.250
9	0.192	0.249	0.371	0.293
10	0.407	0.155	0.238	0.200
11	0.326	0.178	0.150	0.326
12	0.290	0.239	0.301	0.206
13	0.237	0.178	0.232	0.224
14	0.314	0.200	0.373	0.280
15	0.471	0.182	0.256	0.236
$\overline{X} \pm SD$	0.281±0.10	0.188±0.04	0.289±0.07	0.247±0.04

3.4 Microscopic Structure of Peel

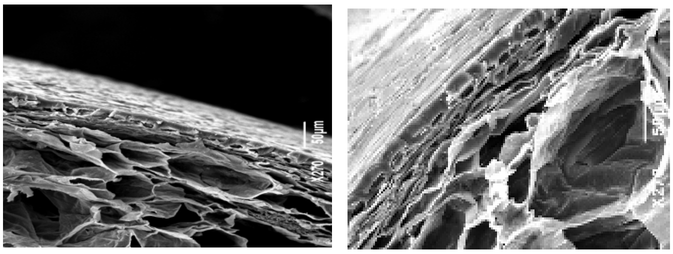
Figure 8 shows scanning electron micrographs of the epidermis surface of both kinds of apple peel. It can be seen that microcracks basically do not exist on the Starkrimson sunlit peel, while on the other side there exist more microcracks with a net-like distribution and the microcracks' fracture surfaces are neat. Meanwhile, there exist microcracks on both sides of the Fuji peel in a parallel arrangement and the surface is not neat. The number of microcracks on the sunlit side is far smaller than on the shadow side.



(a) Starkrimson sunlit, (b) Starkrimson shadow, (c) Fuji sunlit, (d) Fuji shadow.

Figure 8 Scanning electron micrographs of the apple epidermis surface.

In Figure 9 shows the microscopic structure of cross-sections of both apple cultivars. In the cross-section images it can be seen that the apple peel consists of a cuticle, epidermis cells and epithelial cells. A corneous layer covers the outer surface epidermis cells, with the epidermis cells protecting and preserving the fruit [28]. As can be seen from Figure 9(a), the cuticle layer of the Starkrimson peel is bumpy and has a shallow V sag, while the epidermis layer is composed of a single layer of cells whose shapes are circular or elliptic. From Figure 9(b) it can be observed that the cuticle of the Fuji peel has a uniform and consistent arrangement. The epidermal cell layer is also a single layer and its cells are shaped like long strips.



(a) Starkrimson (b) Fuji

Figure 9 Cross-section microstructure of apple peels.

Table 4 contains the microstructure indexes of both kinds of apple peel. The thickness of the cuticle layer, the size of the epidermis cells and the distance between them are different for the two varieties but the organization structure of the peel is the same. The experimental measurements showed that the Starkrimson epidermal cells are circular or elliptic, while the Fuji epidermal cells are elongated. The cuticle layer thickness, length-width ratio of epidermal cells, and microcrack width of the Starkrimson peel compared to the Fuji peel are smaller, while its epidermal cell spacing is bigger compared to the Fuji peel.

In our preliminary study on peel mechanical properties, it was discovered that there is a non-significant effect of the peel mechanical properties on the thickness of the cuticle and a negative effect was found for the aspect ratio of the epidermal cells. Moreover, a negative effect was found for the width and quantity of microcracks on the peel. The circular or elliptic cells of the peel have a higher tensile strength than the elongated cells. Tissue composed of big cells has a lower compressive strength and modulus of elasticity than tissue with smaller cells [36]. A more round cell formation may provide higher rupture stress than peel formed by elongated cells [2].

Table 4 Parameters of microstructure on apple peels.

Parameters	Starkrimson apple	Fuji apple
	Mean value (min-max)	
Cuticle thickness/μm	12.86 (10.37-18.52)	13.78 (10.49-17.36)
Epidermal cells length/μm	16.30 (12.53-24.00)	23.80 (13.56-52.11)
Epidermal cells width/μm	8.48 (5.98-12.38)	7.60 (4.00-10.89)
Ratio of epidermal cells	1.93 (1.49-2.43)	3.32 (2.01-6.82)
Peel cell spacing/μm	7.42 (5.16-10.89)	6.18 (4.33-7.60)
Peel microcrack width/μm	5.68 (2-11.02)	7.28 (2.88-17.02)

4 Conclusions

In this study, the biomechanical characteristics of peels from two apple cultivars were studied. Three measurement methods were successfully applied in order to test tensile strength, elastic modulus, fracture strain, tear strength and puncture strength. When the peel is under tensile stress, the stress-strain curve presents an approximate S-shape, which provides some reference to build a nonlinear model of the peel material. The peel breaks at fruit spots, which reflects that the fruit spots are stress concentration points on the peel. For the same cultivar, the elastic modulus and puncture strength of the longitudinal samples showed a significant difference from that of the transverse samples. As for the difference between both cultivars, it was observed that the tensile strength of the Starkrimson samples was significantly greater than that of the Fuji samples. These cases show that the apple peel is an anisotropic heterogeneous material. The ability to resist deformation was higher for the Starkrimson peel than for the Fuji peel. The susceptibility to damage of the Starkrimson peel was below that of the Fuji peel, where the resistance to penetration of sunlit peel was stronger than that of shadow peel. These results can provide some reference for the design of apple harvesting machines.

Based on the scanning electron micrographs, it can be concluded that the mechanical properties are closely related to the peel microstructure. The strengths and weaknesses of the mechanical properties depend mainly upon the number and width of microcracks on the cuticle, cell shape, and space between cells in the epidermic layer. Moreover, knowledge of the relationship between the macroscopic mechanical properties and the microstructure of apple peel can help to cultivate good varieties of apple.

Apple peel plays a role to protect and preserve the fruit as a first line of defense and its properties are closely related to fruit storability. Therefore, based on the results of these mechanics tests and the micrographs, the Starkrimson peel is the better model when developing biomimetic materials.

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